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INVESTIGATIONS ON LIGHT AND HEAT, MADE AND PUBLISHED WHOLLY OR IN PART WITH APPROPRIATION FROM THE RUMFORD FUND.

XII.

AN ACCOUNT OF A NEW THERMOGRAPH, AND OF SOME MEASURES IN LUNAR RADIATION.

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Presented by Professor Trowbridge, March 13, 1889.

DURING the winter of 1886–87 the writer carried out at Cambridge a series of experiments with the bolometer and other sensitive heat-measuring devices, the intention being, if the apparatus could be made to perform satisfactorily, to attempt the solution of some problem in radiation. One in particular in mind was that of the radiation from rocks, as important from a geological standpoint. It was also thought possible that the work might be made a valuable supplement to Langley's investigations in lunar radiation.

After two or three months of preliminary experimentation the matter was abandoned, and the further pursuit of the subject was not undertaken until October, 1887. In designing a working apparatus for use in the research thus resumed, some modification of the thermopile suggested itself, and a contrivance was finally adopted constructed upon the principle embodied in that familiar instrument. This new device possesses the sensitiveness necessary for accurate and delicate work, and at the same time is very simple in operation. This last is an important feature, for in all instruments intended for measuring small quantities of heat the matter of simplicity is a very grave one. It hardly needs saying, that the number of the parts in the instrument should be limited to as few as possible, and that the whole should be as simple as it can be made. Multiplication of parts leads to inaccuracy in performance with almost absolute certainty. It is the element of simplicity that has, until recently, rendered the ordinary thermopile the most successful instrument possible to be employed in dealing with small quantities of heat. The failings of the thermopile, however, are so numerous and so fatal that it becomes an instrument of precision in the hands of a very few, who must serve a long apprenticeship in its use.

Impressed with the number of the difficulties which beset the use of the thermopile, the writer set about a systematic study of the conditions necessary to their removal. It was soon observed that a great advantage could be gained by employing a single thermal junction, instead of many, and by condensing the heat rays upon this one by means of a concave mirror. All of the advantages of the thermopile are thus retained, while its most serious failing — the slowness with which the large mass of metal presenting the sensitive surface parts with its heat — is obviated altogether. The condensing mirror fulfils the function of multiplied junctions, while the single union of bars employed in the new instrument rapidly attains thermal equilibrium under any series of conditions.

This preliminary proposition having been laid down, — that a single junction of two metals, suitably supplemented by a concave mirror, can be made as effective as a larger number of junctions without the mirror, — various experiments were next undertaken with a view to ascertaining the best form for the single junction, as well as the most suitable materials to enter into it. With these ends in view a great number of unions were made, including some very delicate combinations into which tellurium was introduced. The bars of metal used in these experiments were made very thin, and in attempting to form certain junctions great difficulty was experienced; for when very thin bars of easily fusible metals are to be soldered together, it is sometimes almost impossible to perform the act properly, without melting the bars. In such cases the electro-deposition of silver or copper in the junction succeeds admirably.

As the outcome of these experiments it was learned that the best results could be obtained from a junction formed by two of the stronger metals, worked into very thin strips, the opposite ends of the metal ribbon thus formed being attached to copper rods — the terminals — with the point of junction midway between. The reasons for such a construction and the advantages especially to be derived from it are briefly these. It is plain that a thin strip of metal will not only take up and part with its heat in a much shorter period of time than will a thick bar, but that it will also, in a given interval, be raised to a much higher temperature than the thick bar. The strong metals are employed for the obvious reason that the brittle metals cannot be made into very thin leaves and at the same time remain self-sustaining. Further, thin strips of even such metals as iron and copper, the thermo-electric force of which is comparatively feeble, brought into conjunction, give a greater electric current when excited by a feeble radiation than is obtained from a junction of bars of antimony and bismuth under similar circumstances. Finally, to employ a condensing mirror having the junction at its focus is simpler than to multiply the number of junctions, and, moreover, it adds nothing to the resistance of the circuit.

INSTRUMENTS.

The Thermograph.

There will now be described, in detail, the instrument which was the outgrowth of the principles touched upon above. It is not beyond the power of one possessed of very ordinary mechanical skill, and who may be perforce his own instrument-maker in matters like the present. The measures will be given in inches, since most workmen still employ that unit.

A cylinder is turned from vulcanite, or some hard wood, 3 in. long and 1 in. in diameter. For $\frac{3}{4}$ in. at one end this cylinder is made of less diameter by $\frac{1}{16}$ in., in order that it may receive and hold firmly a piece of brass tubing 3 in. long, 1 in. in external diameter, and $\frac{1}{32}$ in. thick. The end of the cylinder carrying the tube will be designated in what follows as the " front end." The cylinder is next pierced, in the direction of its length, with two $\frac{1}{8}$ in. holes lying upon the same diameter and $\frac{7}{10}$ in. apart. Through these holes copper rods are firmly driven, being left to project $\frac{1}{2}$ in. above the front end of the cylinder. They are allowed to project $\frac{3}{4}$ in. from the back end of the cylinder, and are afterwards bent apart somewhat to facilitate the attachment of screw cups. The front ends of the rods are made somewhat smaller than the other portion by filing.

The thermal junction is made as follows. Some bits of rather wide watch-spring are procured, together with some rolled sheet nickel. A strip of the same width as that of the watch-spring is cut from the nickel, and, the ends of the spring and of the piece of nickel having been scarfed with a file, the two are united by means of the strongest hard solder obtainable. For convenience in handling, it is well to leave the piece of watch-spring long. The compound strip can now be made straight upon the edges, and worked thin with a fine file. Trial is occasionally made with a screw caliper, and when the thickness has been reduced to .02 mm. it is best to discontinue. The solder junction must be very perfect, or it will be pulled apart in the filing. With great care and patience the thickness of the strip of metal can be reduced to .01 mm., but there is no compensating advantage for the labor expended. When finished, the wide strip can be cut with scissors into several narrow bands, and preserved in a dry bottle.

To complete the thermograph, a strip is selected from the stock, laid across the rods at the front of the cylinder, and secured in place with a little soft wax. The wax permits the strip to be shifted, until it is proved by measurement that the junction is exactly midway between the rods, when the strip is permanently fixed by soldering it to the rods. A small concave mirror of glass, silvered upon the first surface, is now fixed to the front end of the cylinder, between the copper rods, with glue or varnish. The mirror should be ½ in. in diameter and of ⅝ in. focus. When in place, the junction in the metal strip should be exactly at its focus.

The brass tube is carefully blackened within, and is provided with diaphragms, the openings in which are determined by the character of the work for which the instrument is intended. The front end of the brass tube is also furnished with a suitably perforated end-piece of the same material as the cylinder. For some purposes the tube of the instrument requires to be made longer than that of the sample described above, and for other purposes it may be dispensed with. For linear measurements, as in spectrum work, it is only necessary to replace one or more of the diaphragms by slits at right angles to the direction of the strip. The apparatus is particularly successful in dealing with small quantities of heat at a point. When employed for this purpose, the condensing mirror is not used, the junction being merely placed behind a small hole in a triple screen, formed by two plates of metal separated by a thick plate of cork or other non-conducting substance.

If for any particular purpose it should be desired to make use of a strip thinner than can be produced by the methods given above, it can be prepared after the following manner. A flat plate of copper is rubbed with graphite and nickel-plated over one half its surface. It is then dried, rubbed with graphite a second time, and the nickel-coated end dipped in melted paraffine nearly to the junction of the nickel and copper. The remaining half of the copper surface can now be plated with iron from a solution of the citrate, the nickel already deposited being protected by its paraffine coating. When the entire thin film is afterward stripped from the copper backing, one half of it will be nickel, the other half iron, and it can be cut into narrow strips as before. The writer has to learn that there is any advantage to be gained from employing strips made in this manner, and they are certainly difficult of manufacture. In general, thin films of electrically deposited metals are hard to manipulate, for they possess the elasticity and brittleness of highly tempered steel, and usually require careful annealing.

The Galvanometer.

The galvanometer intended to accompany the heat-measuring device should receive as careful attention as the device itself. The writer had had some previous experience in the construction of sensitive galvanometers before attempting the research of which the present article is an account; nevertheless, several different forms were tried before one was found exactly adapted to the thermograph. The requirements to be met were, in brief, first, considerable sensitiveness, and secondly, rapidity of working, — qualities which are to some extent incompatible, but which have, as far as possible, been combined in the instrument in use. It would have been possible to produce an instrument much more sensitive than the one actually employed, had the rate of working been left out of account; but nothing is more annoying than to be obliged, when time is precious and opportunities for observation are perhaps few, to wait for a galvanometer needle to come to rest; consequently the element of time has had the first consideration.

The galvanometer adopted for use with the thermograph has four coils, each containing about four feet of wire 0.063 in. in diameter. The wire was twice shellacked and baked before being wound. The coils are contained between brass plates, which constitute the body of the instrument, the inner faces of the two plates, which are in contact, being grooved for the passage of the staff of the needle and its supporting silk fibre. The needle thus swings in an entirely closed space but little larger than itself, and needs no damping vanes to bring it quickly to rest. Two minute scales of mica are attached to the needle to prevent it from being turned completely round. The astatic system has the magnets fixed upon a very slender aluminum staff two inches in length. The magnets are from $\frac{1}{4}$ in. to $\frac{3}{8}$ in. in length, and very slender. The mirror is flat, and $\frac{3}{8}$ in. in diameter. Much of the success of the instrument depends upon the perfection of the mirror. It is difficult to obtain perfectly plane mirrors, and, moreover, those to be had in the market are too heavy. They can be made, of great perfection, by selecting a perfectly flat piece of thin plate glass, cementing it to a thicker piece of glass for a support, and then grinding it down to the thickness of stout letter paper. A very thin sheet of glass is thus obtained, from which circles of the required size can be cut with a diamond. The glass being now silvered upon the surface, the polish of which was not destroyed by the grinding, we have a first surface reflector which will bear a high magnifying power if the mirror be not strained in mounting.

The scale is read in a novel manner. The cell in which the mirror swings is closed by a bit cut from the centre of an ordinary spectacle lens of from 36 to 48 inches' focus. The scale is located as in the ordinary arrangement of telescope and scale, but instead of the telescope we have the following device. A tin or paper tube is provided, and in it, at a distance of five inches from one end, is placed a lens, three inches in diameter, and of six inches' focus. The end of the large tube has a draw-tube, which is closed by a metal plate provided with a peep-hole at its centre. The peep-hole may be made to occupy the focus of the lens by sliding the draw-tube backward or forward as required. A horse-hair or very fine wire is stretched across the tube in the focus of the lens opposite the draw-tube, so that it may be clearly seen by the eye applied to the peep-hole. This arrangement is to be mounted in the place occupied by the ordinary telescope, which it far surpasses both in definition and in the breadth of the field of view. The whole apparatus when in position opposite to the galvanometer constitutes a telescope, of which the lens in the galvanometer is the object-glass, the large lens in the tube the eye-piece, and the scale the object viewed. The definition is quite remarkable, the fibre of the paper upon which the scale is ruled showing clearly, as though seen through a magnifying-glass.

The details of construction of the entire apparatus having thus been outlined, it remains to speak of the action of the whole. As an example of the accuracy that may be expected in the performance of the instrument, the following test may be taken.

October 23d, 1888, the sun was taken as a source of heat, the rays being reduced by passage through a small opening. The following galvanometer deflections were obtained: —

	Divisions.		Divisions.
First	162	Sixth	164
Second	162	Seventh	162
Third	161	Eighth	161
Fourth	162	Ninth	161
Fifth	162	Tenth	162

The observations were taken rapidly, occupying less than ten minutes in all.

No great effort has been made to secure superior sensitiveness, yet the heat from the face of a person at a distance of fifty feet is measurable. A comparison was made between the thermograph and a thermopile of forty-eight couples. Using the same galvanometer for each, the thermograph proved about twelve times as sensitive as the other instrument. The limit of sensitiveness could be very much extended, if it were desired, by the use of a more delicate galvanometer. As actually adjusted, the galvanometer employed gives a deflection of one scale division for 0.00000007 Ampère, the period being ten seconds. The constant of Langley's galvanometer was 0.0000000013 Ampère, or fifty times less.

RADIATION FROM ROCKS.

As experiments upon the radiating power of rocks and minerals were the first in which the new instrument was employed, they will be first discussed.

The want of a standard of radiation which should be more satisfactory than a lamp-black-coated surface was seriously felt in these experiments. Lamp-black is a hygroscopic substance, and radiates differently when in different states, unless it be applied with sufficient varnish to make it water proof. But if it be mixed with the smallest possible amount of varnish, and applied to a surface, then the radiating power is different from that of the same surface coated by camphor smoke. Also, it appears to radiate differently when applied in the same manner to different substances. The writer has always found ordinary white pumice-stone a better radiator than the same blackened. There is no other instance in which so variable and imperfect a *standard* is tolerated. The writer has employed as a working standard in these experiments a piece of pure quartz finely ground with emery but unpolished. Such a standard seems to possess many advantages. Quartz is readily obtainable in a pure state. It is imperishable and unalterable at any ordinary temperature. It has the great merit of perfect definiteness of composition.

The measures of radiation from the rocks were made as follows. Each specimen had a wooden handle adapted to it, for convenience in handling when hot. The rocks were heated in an oven intended for drying chemical precipitates. The oven was of heavy iron, and was heated from beneath by numerous small gas jets. It was found that, after the gas had been lighted about an hour, the temperature of the oven became constant, and remained so for any length of time. The rock under experiment and the quartz standard were placed in the oven together, side by side, and after the lapse of an hour they were removed, first the quartz and then the rock being quickly taken from the oven, presented before the opening in the thermograph, and the deflection noted. The specimens were then returned to the oven, and some time allowed to elapse before the experiment was repeated. In this way as many measures were obtained from each specimen as could be made in the course of a day, i. e. from ten to thirty. The method seems far from perfect, but it was the best of several that were tried.

To reduce the results to the lamp-black standard, a very careful comparison was made between the radiating powers of blackened and unblackened faces of the quartz. The temperature at which the measures were made was near 100°. The results are given in the following table, the radiation from a blackened surface of quartz being taken as 100.

Name.	Locality.	Character.		Radiating Power.
Lava	Hawaii	Imperfectly fused.	Black	91.2
Lava	Vesuvius	Dense.	Gray	90.4
Lava	D'Auvergne	Basaltic.	Dark	81.8
Lava	D'Auvergne	Scoria.	Light red	86.5
Lava	Hawaii	Well fused.	Red	91.9
Pumice	. . . . .	Common.	White	71.3
Lava	Vesuvius	Vesicular.	Black	86.3
Scoria	Vesuvius	Very light and porous.	Black	91.6
Pumice	Vesuvius		Red	89.1
Trap	Nova Scotia		Dark	83.2
Trap	Mt. Kineo		Light gray	94
Obsidian	. . . . .		Black	88.5
New Red Sandstone	Pembroke	. . . .		89.3
Flexible Sandstone	Georgia		Red	85.9
Slate	Pennsylvania	From coal beds, with pyrite.		89.8
Slate	Georgia		Red	84.1
Feldspar	Topsham, Me.		Pure white	88.5
Gypsum	. . . . .		Pure white	86
Iceland Spar	. . . . .		Pure	85
Mica	Hebron, Me.	. . . .		76.3
Serpentine	. . . . .	Common.	Green	89.1
Quartz	. . . . .	Pure.	Transparent	90.8
Amphibole	New York	Common.	Green	91.4
Tremaolite	. . . . .		Pure white	85.5
Pyrite	. . . . .	. . . .		76.4
White Marble	. . . . .	. . . .		86.7
Mica Schist	. . . . .	. . . .		80.8
Granite	. . . . .	Fine-grained.		93.5

An inspection of the table shows a remarkable uniformity in radiating power for materials so diverse in character. The large number of volcanic rocks was selected, because it seems probable, from its physical features, that the rocks of which the surface of the moon is made up are of volcanic character.

LUNAR RADIATION.

While the light received from the moon has been frequently measured by many different observers, the more important problem of its dynamic radiation has been solved by but a single person. Observers previous to Langley can pretend to so little accuracy in their results, that our knowledge of lunar radiation may be said to rest upon his authority alone. This condition does not arise from any lack of interest in the subject, — on the contrary the problem has always been a fascinating one, — but is due to the fact, that, previous to the invention of the bolometer, no instrument existed capable of dealing accurately with so small an amount of heat as the moon affords. Great interest, therefore, cannot fail to attend the results of careful observation, made with competent instruments, and tending to increase our knowledge of the subject.

The first trial of the new thermograph on the moon was made on January 27, 1888. The apparatus, tested at that time, has been regularly employed since, and has performed so satisfactorily that it has scarcely been altered from its original form. The arrangement of the thermograph for the measurement of lunar radiation is this. An oblong box of pine wood carries at one end a silvered glass mirror, 0.196 metre in diameter, and of one metre focus. This mirror is adjustable by screws passing through the end of the box and bearing upon its back. Near the other end of the box is fixed a grooved block, upon which the thermograph may be placed and secured. The block is also provided with adjusting screws, so that the thermograph may be made to point exactly at the centre of the mirror. The mirror is inclined, so that the moon's image is thrown into the opening of the thermograph, and brought to a focus upon the strip. The whole arrangement is that of a Herschel's telescope with the thermograph in place of an eye-piece.

To secure accuracy in pointing, the opening in the thermograph is made of such a size as just to receive the cone of rays from the large mirror, and, a rim of white paper being glued about the opening, the slightest departure from a central position of the cone of rays is announced by the appearance of light upon this paper. A window of plate glass has its place in the side of the box, just in front of the position occupied by the thermograph, and a person looking through this can readily direct the image of the moon into the orifice of the thermograph. A telescope, with cross wires, is also attached to the box, and may be used to direct it, but the former method is much the more satisfactory.

The entire apparatus is mounted upon a massive telescope tripod. The mounting has tangent screw motions, and is provided with a vertical circle for reading the altitudes. An hour or two before it is intended to observe, the apparatus is mounted in the open air, in order that it may have time to acquire the external temperature. Two strands of heavy electric light wire pass from the thermograph to the laboratory, where they are attached to the galvanometer, which is mounted upon a firm pier.

For some reasons the effect of phase should precede all other considerations as a subject of investigation, but it has been postponed until later. The subjects that have engaged our attention, up to the present time, may be for the most part classed under two heads: 1. The comparative intensity of radiation of the full moon and of the sun. 2. The absorptive effect of the earth's atmosphere upon the radiation of the moon. These two topics will be considered in turn.

It is obviously impossible to confine the observations to the time of full moon without giving undue time to the investigation; hence the effect of phase demands to be considered. To avoid the introduction of errors from this source the following precautions have been taken: 1. To confine the observations to the three days nearest full moon. 2. To measure always the radiation from a constant area of the moon's surface. To fulfil the conditions of the second precaution, there is placed, close to the strip of the thermograph, a diaphragm, the opening in which is much smaller than the moon's image which falls upon it. Thus there may be a large change of phase, and the opening still remain full of the moon's image. This arrangement would completely remove the difficulty, provided that the moon reflects like a flat disk, as Zölner thinks, — which is not at all certain. It is believed, however, that, when taken in connection with the first precaution, the outstanding error cannot be large. The method has the disadvantage of reducing the available heat by about one half; but, as it is, the heat is sufficient to drive the needle off the scale with the galvanometer in its most sensitive condition. The controlling magnet is set so that a deflection of between one and two hundred scale divisions is obtained, corresponding to a period of between five and ten seconds' vibration of the needle.

One observer being stationed at the galvanometer, and a second at the instrument out of doors, at a signal from the first, the latter brings the image of the moon into the opening of the thermograph, and the deflection occasioned is noted and recorded by the observer at the galvanometer. In this manner a set of ten readings is taken, and, the altitude of the moon being measured at the beginning and the end of the set, the mean of the ten deflections is taken as the deflection corresponding to the mean altitude. About six minutes are required to make a set of the readings.

The following series, selected at random from the observation-book, will serve as an example of the results obtained.

DATE. — FEBRUARY 24, 1888.

Mean Altitude.	Mean Time.	Deflection.	Mean Deflection.
52° 40′	7 h. 34 m.	....	....
....	....	171.5	....
....	....	172	....
....	....	168.5	....
....	....	166	....
....	....	171	....
....	....	174	....
....	....	172	....
....	....	175	....
....	....	173.2	....
....	....	175	....
....	....	....	171.8

The probable error of a single observation, when the moon is the source of heat, is considerably greater than is the case with an artificial source, or even with the sun. The cause is, in part, due to invisible clouds of vapor floating in the atmosphere, as Langley thinks. It has been observed that immediately after rain this effect is particularly noticeable, even when the sky appears perfectly clear to the eye. There is another cause, which doubtless exerts a large influence; that is, the irregular radiation of different portions of the moon's surface. It has been found* that, photographically, the mean brightness of the dark region is to that of the bright region in the ratio of 55 to 100. We might be prepared to expect large differences in the radiant energy of the respective regions, and the average radiation may therefore be more closely attained from a series in which the individual readings vary considerably, than from a more perfectly concordant set.

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* Annals of Harvard College Observatory, Vol. XVIII. No. IV.

Having obtained a sufficient number of sets, as perfect as may be, we have next to effect a comparison between the deflections produced by the moon, and the deflections brought about by the sun under similar circumstances of observation, — such as altitude, height of barometer, etc. The heat of the sun's rays must be reduced in some manner in order to bring them within the range of the same instrument employed in measuring the feeble radiation of the moon. Both Lord Rosse and Langley accomplished the reduction by passing the sun's rays through a small opening, and placing the heat-measuring appliance in the diverging beam.

The enormous differences that appear in the results of observers who have measured the light of the moon, and compared it with sunlight, put us upon our guard against sources of error, and impressed upon us the necessity of going over the ground by independent methods. Let us consider the probable sources of error in the above mentioned method of comparison: —

1. Errors of observation. These are small, and can be reduced to any extent by repeating the observations.

2. Absorption by the mirror, used in condensing the lunar rays. The mirror is always kept perfect by frequent silvering, and a flat mirror, silvered by the same process, is employed in reflecting the sun's rays to the small opening.

3. The plate of metal in which is the perforation becomes a source of heat when the sun's rays are thrown upon it, and would increase the heat indication. This effect is avoided by placing the thermograph so far from the metal plate as to render its influence practically imperceptible.

4. Effect of diffraction at the opening. Unknown.

As an example of the results obtained by this method, let us take the observations of April 25 and 26, 1888.

On the night of April 25, the deflection produced by the moon at an altitude of 42° was 184.8 scale divisions.

We have also:

Semidiameter of condensing mirror	. .	95 mm.
Focus " "	. .	1000 mm.
Semidiameter of moon, augmented	. .	17′.

Hence we have, for the concentration of the moon's rays,

$$\frac{\overline{95}^2}{(1000 \times \sin 17')^2} = 369.1.$$

Had the moon's rays, uncondensed, acted upon the thermograph, the deflection would have been:

$$\frac{184.8}{369.1} = 0.5008 \text{ scale divisions.}$$

On the following morning, the altitude of the sun being 42°, its rays were reflected through a small opening, and being received by the thermograph, placed at a distance, a deflection of 147.16 scale divisions was found to be the mean of 30 readings. The opening through which the sun's rays were reflected was a carefully reamed hole in a metal plate. Its diameter, being measured under the microscope, with the aid of a stage micrometer which purported to be divided into tenths and hundredths of a millimeter, was found to be 1.67 mm. A paper screen received the spot of light, formed by the rays from this opening. The diameter of the spot was 40.6 mm. The thermograph was thrust through an opening in the screen until its strip lay in the plane of the paper. The spot of light could then be thrown into it by turning one of the screws of the heliostat.

We have for the reduction of the sun's rays:

$$\frac{\overline{40.6}^2}{\overline{1.67}^2} = 615.3.$$

Had the thermograph received the undiminished sunbeam, the deflection would have been:

$$615.3 \times 147.16 = 90596.$$

The ratio of the sun's radiation to that of the moon is, therefore,

$$\frac{90596}{0.5008} = 180{,}900.$$

Second Method.

In the second method, the sunbeam is employed without diminution, but its effect is reduced by interposing a resistance in the galvanometer circuit. This method is free from all objections, as far as can be seen, for its accuracy depends upon the measurement of a resistance, an operation which can be accomplished with great accuracy. Moreover, it removes any effect due to minor disturbing causes, such as the heating of the metal plate in the first method, since, when a large resistance is interposed, the apparatus becomes insensible to such influences.

The resistance of the thermograph, galvanometer, and the connecting wires, is 0.2095 ohm. On October 21, 1888, the sun's altitude being 31°, 100 ohms were added to the resistance of the circuit, and when the sun's rays were thrown directly into the thermograph a deflection of 114.6 scale divisions was obtained. Without the 100 ohms of additional resistance, the deflection would have been:

$$\frac{100 \times 114.6}{0.2095} = 54700 \text{ scale divisions.}$$

That same evening the moon was observed at an altitude of 30° 15′, the deflection being 124.59 scale divisions. From its augmented semi-diameter, 14′ 52″.7, and the same constants as in the previous example, we find the deflection for the uncondensed moonbeam to be 0.2945 of a scale division.

The ratio of 54700 to 0.2945 is 186,300. The results obtained by the two methods are here tabulated.

Ratio of Sun Radiation to Moon Radiation.

First Method.		Second Method.	
March 30, 1888 . . .	181,000	October 18, 1888 . . .	187,200
April 25, 1888	180,900	October 21, 1888 . . .	186,300
October 18, 1888 . . .	167,400		

Mean of the five results 184,560

The results given by the two methods do not show the wide disagreement so noticeable in the comparative light of the two bodies, as found by different methods. This fact is strong evidence in favor of the accuracy of the mean result. In reality, the problem of the total comparative radiation of the sun and moon is in many respects simpler than the problem of the comparative light intensity of the two bodies. In the former case, there is freedom from all personal bias; the measurements are all given by the indications of the instruments directly, and, in general, the chances for error seem to be fewer.

Lord Rosse found the ratio of solar to lunar radiation to be 80,000 to 1. Langley obtained the ratio 96,509 to 1. Provided the moon were a flat disk, reflecting perfectly all of the sun's rays that fall upon it, we could not receive more than one 97,000th part of the solar heat from such a disk, as Zölner has shown. The close agreement of his result with this number Langley considers to be largely a matter of chance, or, rather, of constant errors, tending in an unknown degree to increase the observed values.

It would be *a priori* quite improbable that we should, under the circumstances of reflection from the lunar surface and subsequent passage of the reflected rays to the surface of our planet, receive anything like the maximum possible radiation. Our atmosphere cuts off a considerable portion of the lunar rays. It has been observed that aqueous vapor is particularly efficacious in stopping them. It may not be uninstructive, as illustrating the minuteness of the quantity of heat that we receive from the moon, to express it in terms of melting ice. It will not be far from the truth if we say that the sun's rays will thaw through an inch of ice in 100 minutes, whence it follows, from our determination, that the rays of the moon will melt the same thickness of ice in 18,456,000 minutes, or 35 years.

That portion of the solar rays not reflected from the lunar surface is absorbed by it, and radiated at different wave lengths. At what wave lengths we do not know, and whether or not those rays are capable of passing our atmosphere we cannot tell. An idea of the general character of the lunar rays may be gained from experiments with absorbing media. For example, on April 25, 1888, the percentage of lunar rays transmitted by a plate of quartz was determined. The quartz plate was 5 mm. thick, cut perpendicularly to the axis of the crystal. It was arranged to be drawn before the thermograph by a thread, so that the observations could be made in pairs, alternately with and without the quartz. The results were as follows : —

Moon's Altitude.	Deflection through Quartz.	Deflection without Quartz.	Per Cent transmitted.
13°	38.4	137.2	34.6
19°	54 4	157.0	27.9
24° 30′	51.3	163.2	31.4

Mean of the whole (60 readings) . . . 31.3%

An attempt was then made to find some artificial source of heat whose radiations would be transmitted by the plate of quartz to the extent, approximately, of 31%. It was discovered that a coil of platinum wire, in a Bunsen lamp, turned as low as possible, very nearly fulfilled the requirement. We may say, then, that in general character the rays from the moon resemble those from an incandescent platinum wire. The plate of quartz used in the above experiments transmits 93.3% of the sun's rays.

A study of the reflection of the sun's rays from rocks may serve, to some extent, to aid in the lunar problem, and to this end a few experiments have been made, after the following manner.

The thermograph is mounted upon a strip of board, which can be turned about a pin passing through it and into the table below. The rock under experiment is held in a clamp a short distance in front of the instrument. The board bearing the thermograph is moved about the pin by drawing upon a cord, and is brought back to place by an opposed spiral spring. Should it not be desired that the thermograph remain continuously exposed to the radiation from the rock, it may be turned away from it by a pull upon the cord. When a reading is to be made, the cord being released, the spiral spring draws back the board, which is stopped at the proper position by a pin fixed in the table. The rock under examination is given a flat surface by grinding it upon a sheet of glass with emery. The sun's rays are directed upon it by a heliostat, the diameter of the solar beam being limited to 26 mm. by a circular diaphragm.

On November 4, 1888, a slab of white marble was made the subject of experiment. The distance from the slab to the thermograph strip was 217 mm. The mean deflection obtained was 82.5 scale divisions. Had the marble slab reflected perfectly in every direction the solar rays that fell upon it, the ratio of the radiation received at the thermograph strip to the solar radiation would have equalled the ratio of the area of the cross section of the solar beam employed to the area of the hemisphere of which the distance from the marble to the thermograph strip is the radius; or,

$$\frac{82.5}{\text{Solar Radiation}} = \frac{\pi\,\overline{13}^2}{2\,\pi\,\overline{217}^2}.$$

From which we find, Solar Radiation = 45980 scale divisions, upon the supposition of perfect reflection by the marble.

The thermograph was next placed in the direct solar beam, with a resistance in the galvanometer circuit, and the true solar radiation was found to be measured by 84170 scale divisions of deflection. Hence, of the solar rays falling upon it, the marble slab reflected $\frac{45980}{84170}$ part, or 54.6%. In the same manner, it is found that a surface of black slate reflects 38% of the solar rays.

We learn, then, that of the solar rays falling upon rocks a large portion is absorbed and conducted through the mass of the rock, the remaining portion being reflected. In both of the cases given, the sunlight was flashed upon the rock when the reading was to be made, the rock remaining, practically, at the temperature of the room. It appears, therefore, that the solar rays are about equally divided into two portions, one of which is reflected directly, the other absorbed, conducted through the mass of the rock, and radiated in long waves. If the rocks were in large masses, and continuously acted upon by the solar rays, their temperature would be considerably raised by the absorbed heat. The radiation of a body like the moon must consist, in considerable part, of emanations from such a heated surface; and it becomes important to inquire whether our atmosphere is permeable by such rays.

Lord Rosse found, at the time of total lunar eclipse, that with the disappearance of the last ray of light from the vanishing moon radiation, to which his thermopile was sensitive, vanished also. On the night of January 28, 1888, the first systematic observations were made by the writer and his assistants with the previously described apparatus. The moon rose eclipsed. A reduction of the observations shows that

19 minutes before totality the deflection was 11.2 divisions.
8 " " " " " " 7.3 "
During first minute of totality " " 3.2 "

Mean of 30 readings taken during total phase 2.09 "

After the total phase had passed, but while the moon was still in the penumbra, 254.4 was obtained as the mean of 20 readings.

No attempt was made to observe continuously. The evening was so intensely cold, that one could not stand quietly in the open air for any length of time without freezing. The inference to be drawn from these observations is, that all but a minute portion of the rays from the lunar soil and rock are cut off by our atmosphere, for it is impossible to conceive that a surface like that of the moon, upon which the sun has been shining continuously for many days, should suddenly cease to radiate upon withdrawal from the sunshine. It is very questionable, then, if at any time we receive any considerable portion of the radiation from the lunar rocks.

The results given above are in substantial agreement with those obtained by Dr. Boedicker during the same eclipse. He employed a thermopile, and condensed the lunar rays with the three-foot speculum of Lord Rosse. He says,* that, twenty minutes before totality commenced, the heat was reduced to less than five per cent of what it was before first contact with the penumbra. He also observes, that the heat radiated by the moon commences to diminish long before first contact; and that the heat, after last contact with the penumbra, did not mount immediately to what it had been before first contact with penumbra.

It was intended, upon the occasion of the total lunar eclipse of July,

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* Nature, March 8, 1888.

1888, to make as complete an investigation as possible of these and allied matters. With this purpose in view, two complete sets of apparatus were prepared, and two parties of observers were in the field. Upon the night of the eclipse, however, it rained, and observation was consequently impossible.

If we are to conclude that our atmosphere is opaque to radiations from the lunar rocks, we must endeavor to explain the observed behavior of the lunar rays, with reference to absorbing media, upon the hypothesis of selective reflection. We have found that 31% of the lunar rays will pass through quartz; and if it is observed that ordinary rocks absorb and reflect selectively, taking up the short waves, and reflecting the long, the absorption of the lunar rays may be as effectively explained as upon the supposition that we receive radiations from the lunar rocks.

We have arranged to reflect the solar rays from rocks, and, by placing in the path of the reflected ray the same quartz plate that was used in the lunar observations, have ascertained the amount of absorption. The results are shown in tabular form below.

Material.	Mean Deflection without Quartz.	Mean Deflection through Quartz.	Per Cent transmitted.
Red Lava, Porous	153	112	73
Quartz	131	116	88
Black Lava	82	65	80
White Marble	180	147	82
Slate	103	77.8	79
Direct rays of sun transmitted	....	....	93

The results show that selective absorption takes place, but to an extent quite limited, and altogether insufficient to explain the great absorption of the lunar rays. When we consider the great differences in character of the specimens of rocks experimented upon, as compared with the very inconsiderable differences in the transmitted rays, it seems useless to undertake to find a material that shall absorb so large a proportion of the short solar waves that only one third of the reflected rays will pass through the quartz plate.

The question is how to reconcile the results here obtained with the eclipse observations, showing that our atmosphere is nearly opaque to radiations from the lunar rocks. The materials for the solution of this problem do not seem to be at hand. It is, of course, possible that the materials of the moon's surface may absorb selectively to a much greater extent than those that we have examined. On the other hand, if the lunar surface were of very light and porous materials, like our volcanic pumice rocks, a withdrawal of the solar rays might be attended by so sudden a fall of temperature as to explain the eclipse observations. Somewhere between the two the explanation probably lies: but at present we can do little better than conjecture.

Atmospheric Transmission Curve.

An attempt has been made to construct a curve which would show the transmission of the atmosphere for lunar rays at every altitude of the moon. Observations for this purpose have been made, at every opportunity, for nearly a year, and already amount to some thousands in number. It has been customary to begin the observations at moonrise, or, if the moon were already in the sky, as soon as the evening temperature had become sufficiently stationary, and to continue them until culmination.

The working of the apparatus is attended with considerable fatigue, and it is not possible for one person to operate it uninterruptedly. The readings, therefore, are made in sets of ten or twenty with a short rest between the sets. Sometimes a third person has measured the altitudes with a portable transit, while two gave their attention to making the readings; but usually the same person has directed the thermograph-box and taken altitudes at the beginning and the end of each set, the mean reading of each set being regarded as the deflection corresponding to the mean altitude.

Below is given the work of the night of February 28, 1888. Considerable difficulty has been experienced in obtaining the deflections for the high altitudes, as it very frequently happens that, late in the evening, clouds arise from the ocean near at hand and obscure the sky. On this particular evening the sky was very serene and beautiful until 10 h. 40 m., when the clouds arose. Because of this unusual serenity, this series of observations shows more than ordinary regularity, although less than the customary number of observations was made to a set.

FEBRUARY 28, 1888.

Barometer 30.35. *Thermometer* — 13° C.

Altitude.	Time P. M.	Deflection.	Altitude.	Time P. M.	Deflection.
° ′	h. m.		° ′	h. m.	
3 10	7 24	67.2	20 0	9 5	174.3
7 30	7 51	128.6	20 30	9 8	177.5
8 0	7 53	129.4	23 10	9 24	183.1
8 30	7 56	134.5	23 30	9 27	185.3
11 0	8 13	146.6	24 0	9 31	187.1
11 30	8 15	147.5	24 30	9 33	184.1
12 0	8 19	149.0	25 0	9 36	188.1
12 30	8 22	152.2	25 30	9 40	188.3
15 0	8 34	158.3	26 0	9 44	189.0
15 30	8 37	160.3	28 10	9 56	191.0
16 0	8 41	161.6	28 30	9 58	192.0
16 30	8 44	165.1	29 0	10 2	193.4
19 0	8 59	168.1	33 40	10 31	202.1
19 30	9 2	172.3			

To illustrate the effect of the weather upon such observations as these, we may compare with the above the following table, made up from the results of October 21, 1888. On the former occasion the air was very calm, and from its low temperature (—13° C.), must have been quite dry. The evening of the latter date was fine, after many days of fog and rain, and, although clear to the eye save for the merest visible milkiness, the drifting clouds of vapor were made manifest by the irregular transmission of the lunar rays.

OCTOBER 21, 1888.

Altitudes.	Deflections.	Altitudes.	Deflections.
° ′		° ′	
6 45	105.1	20 15	182.7
11 45	146.1	21 0	175.7
12 15	149.1	22 45	178.7
15 45	163.3	29 45	187.8
17 0	159.1	31 0	191.8

Following Langley,* we may find the approximate transmission coefficient for a column of air capable of supporting one decimeter of mercury, by employing the formula

$$t = (M_2\beta_2 - M_1\beta_1)\sqrt{\frac{d_2}{d_1}}.$$

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* American Journal of Science, vol. cxxv. p. 176.

The dates upon which this has been determined, together with the principal quantities entering into the computation, are here given in tabular form.

TABLE OF TRANSMISSION COEFFICIENTS.

Date. 1888.	Altitude (1).	Altitude (2).	d_2.	d_1.	β_2.	β_1.	$M_2\beta_2 - M_1\beta_1$.	t.
	° ′	° ′						
Feb. 28	12 0	33 40	149.0	202.1	7.696	7.676	22.47	0.9866
" 28	15 0	29 0	158.3	193.4	7.696	7.696	13.52	0.9852
March 29	14 54	30 25	112.2	143.4	7.645	7.640	14.42	0.9832
Oct. 18	22 30	41 0	174.5	222.3	7.670	7.670	7.82	0.9708

The mean of the values of t is 0.9852, and t 7.6, the amount of lunar radiation transmitted by the entire atmosphere at the ordinary pressure, is 0.8925.

SUMMARY.

I. We have shown how an instrument may be constructed, capable of measuring very minute radiations.

II. We have measured the radiations of several rocks at near 100°, and presented the results in a table.

III. We have found that the heat which our planet receives from the moon is to that from the sun as 1 to 184,560.

IV. We have compared the lunar rays with solar rays reflected from rocks, with reference to the absorption of each by quartz.

V. We have constructed a curve, representing the change of transmission of lunar rays by our atmosphere with changes in altitude of the moon.

VI. We have found that our atmosphere, at the ordinary pressure, transmits 89.25% of the vertical lunar beam.